IRIS

Integrated Reconfigurable Intelligent Systems

Distributed Intelligence for Automated Survivability (DIAS)
Program Review 10 August 2004

Research Team

Team Leaders:

- ***Aerospace Engineering, Georgia Tech***
  Director of Aerospace Systems Design Lab. Director of the GEAE-University Strategic Alliance for Robust Design Methods and Optimization.

- ***Electrical & Computer Engineering, Purdue***
  Co-Director of Energy Systems Analysis Consortium, Naval Combat Survivability Testbed, Extensive experience in modeling, design and control of shipboard power systems

- ***U. S. Navy, Ocean Engineering Department, MIT***
  Engineering Duty Officer, LPD-17 SUPSHIP Bath, Integrated Power System (IPS), Standard Monitoring & Control System (SMCS)

- ***Weapons & Systems Engineering Department, USNA***
  USN Automation, Systems Engineering, Machinery Control, Surface Ship Engineering & Damage Control Systems, SMCS

Objective:

Design Methods and Tools to System Engineer an Effective and Survivable Integrated Engineering Plant

Motivation: Transformation to an Electric Naval Force

Integrated Reconfigurable Intelligent Systems (IRIS)

Presentation Topics

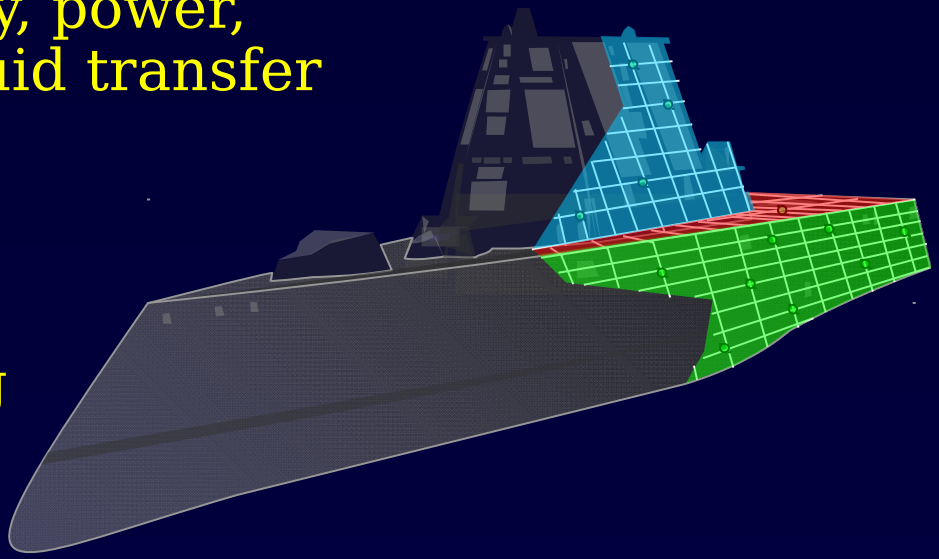
USNA: Navy Need, Continuity of Service Problem Formulation, Integrated Engineering Plant (IEP) Design Baseline, Concept of Operations, Automation Architecture

GA Tech: System Design and Integration, Probabilistic Methods and Tools, Technology Assessments and Multi-attribute Decision Support

Purdue: Performance Metrics, Integrated Engineering Plant Modeling, Evolutionary Design & Evaluation Methodology and Tools

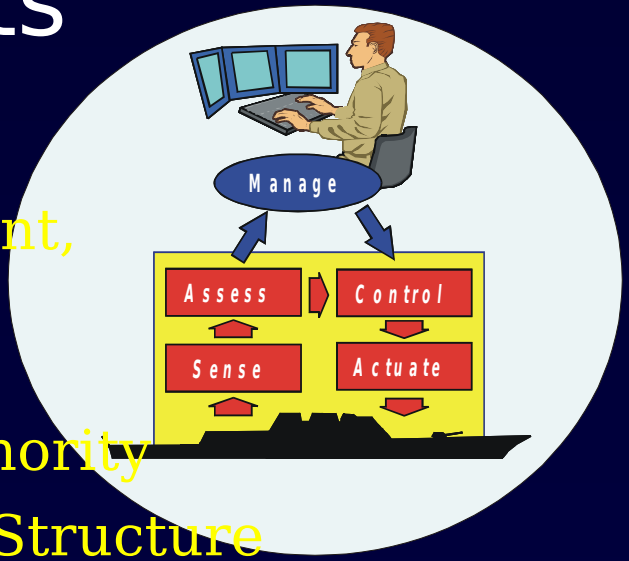
IRIS Integrated Engineering Plant (IEP) Mission Statement

Provide ***continuous*** mobility, power, thermal management and fluid transfer for vital shipboard systems, despite major disruptions involving cascading failures, thereby reducing manning requirements and increasing overall ship effectiveness.



The Integrated Engineering Plant (IEP) integrates a ship's propulsion, electrical, auxiliary and damage control system architectures providing resource management rapid reconfiguration of dynamically interdependent mission critical services under disruptive scenarios, while simultaneously reducing the need for human intervention.

Naval Automation Requirements

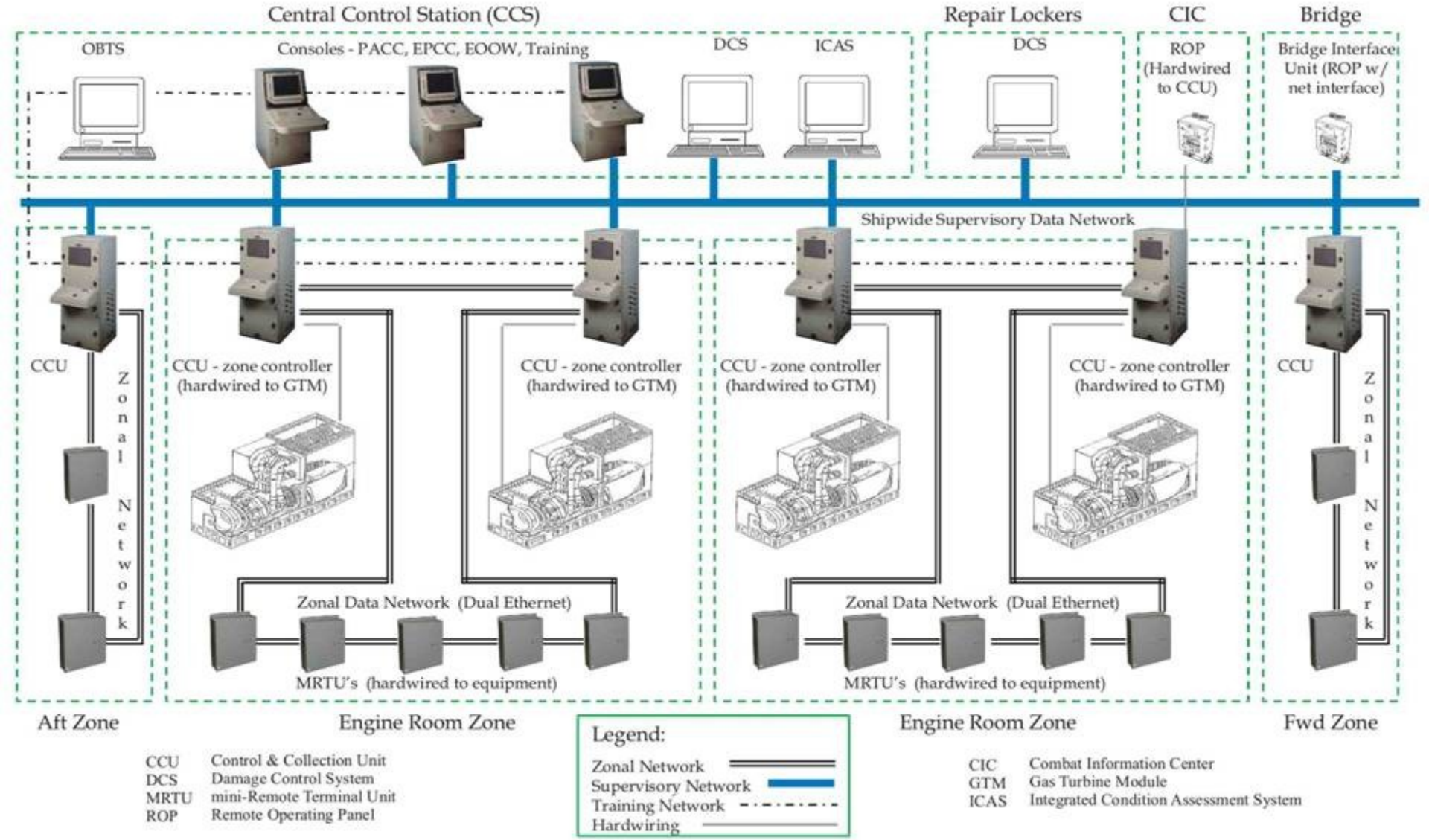


- Continuity of Vital Services:
  Electrical Power, Thermal Management,
  Fluid Transport, Damage Control
- Engineering & Damage Control
  Situational Awareness & Control Authority
- Retain Existing Command & Control Structure
- Condition 1 Casualty Control ⇒ Surge Manning Requirement
- Optimized Manning: 350 ⇒ 200 ⇒ 100:

  ⇒ Reallocation of Human Sensing, Reasoning & Muscle to
  Automation

Dependable

Prior Work: Standard Monitoring and Control System



ONR ⇒ NAVSEA ⇒ Smartship ⇒ LDP-17 • • • ⇒ DD(X)

Integrated Engineering Plant Quality of Service Definitions

Reliability, R: (1) Duration or Probability of failure free performance, Mean Time to Failure (MTBF)
(MIL-STD-721C)

R_M: (2) Probability a system can perform its intended function for a specified time interval (Mission)

Availability, A_O: Probability a system is **operable** and committable for a specific mission including Mean Time To Repair (MTTR) and logistics
(MIL-STD-721C)

Survivability: Ability to ***Avoid*** $(1 - P_H)$ and ***Withstand*** $(1 - P_{K/H})$ hostile damage $P_S = 1 - (P_H \times P_{K/H})$
(OPNAVP-86-4-99)

Susceptibility: P_H probability of being hit

Vulnerability: $P_{K/H}$ conditional probability of being killed if hit

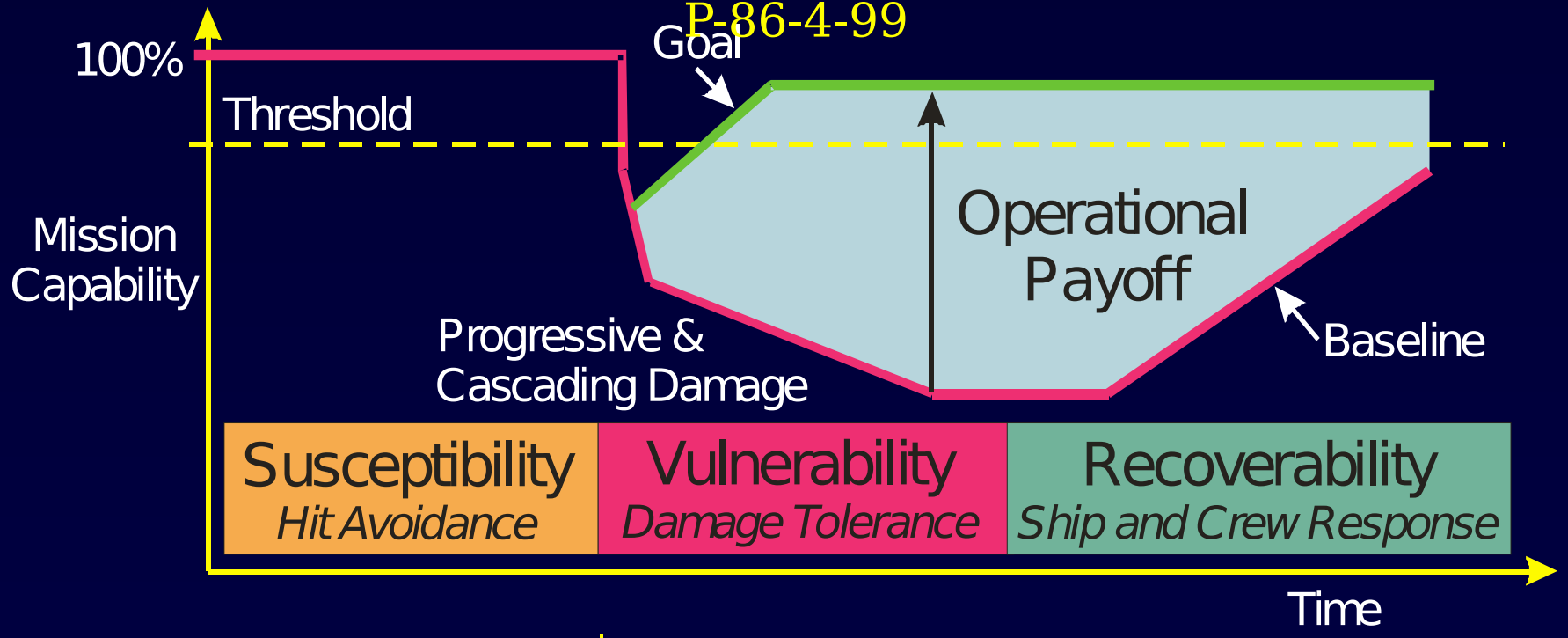
Recoverability: Actions to reconfigure and restore

Operability: Ability to operate throughout a specific damage scenario

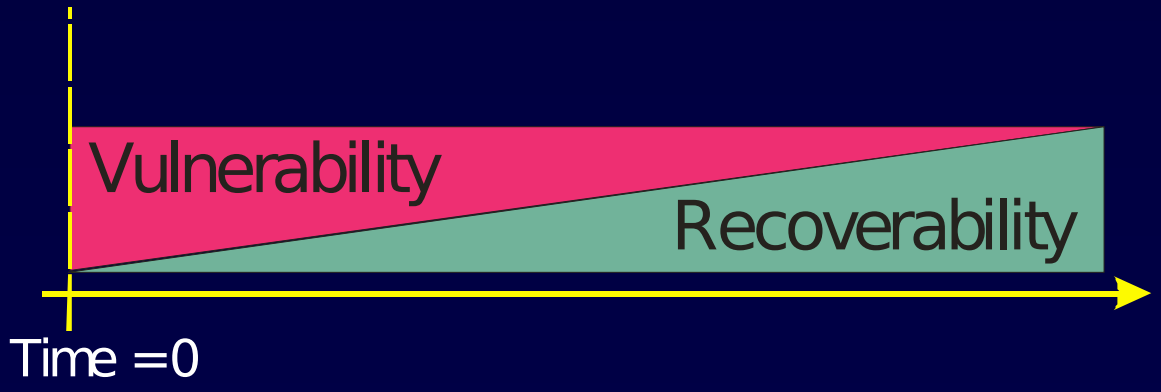
Dependability: Ability to operate throughout a distribution of likely damage scenarios
(*present work*)

Survivability Model

Survivability Design Handbook for Surface Ships OPNAV P-86-4-99



Innovation:
Concurrent Dependability ⇒



Research

Continuity of Service Terms of Reference

Operability: Ability to provide service continuity throughout a specific damage scenario

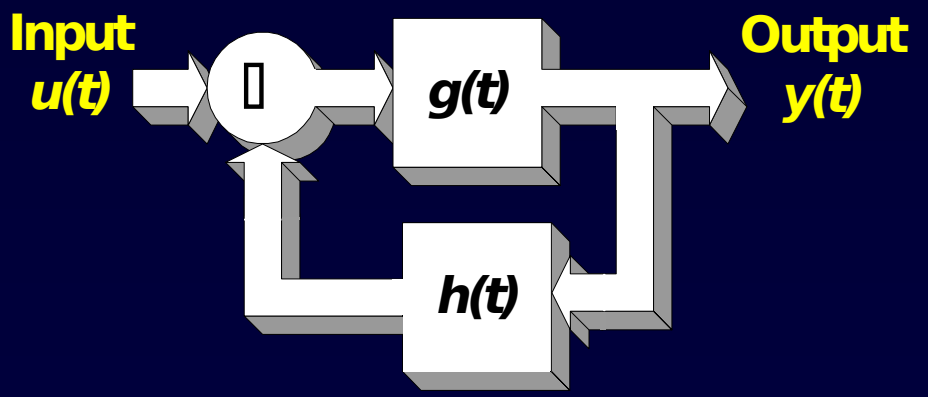
$$O(\boldsymbol{\theta},\boldsymbol{\Omega}) = \frac{\int_{t_o}^{t_f} \sum_{i=1}^{I} o_i(t) o_i^*(t) w_i(\boldsymbol{\theta},t) dt}{\int_{t_0}^{t_f} \sum_{i=1}^{I} w_i(\boldsymbol{\theta},t) o_i^*(t) dt}$$

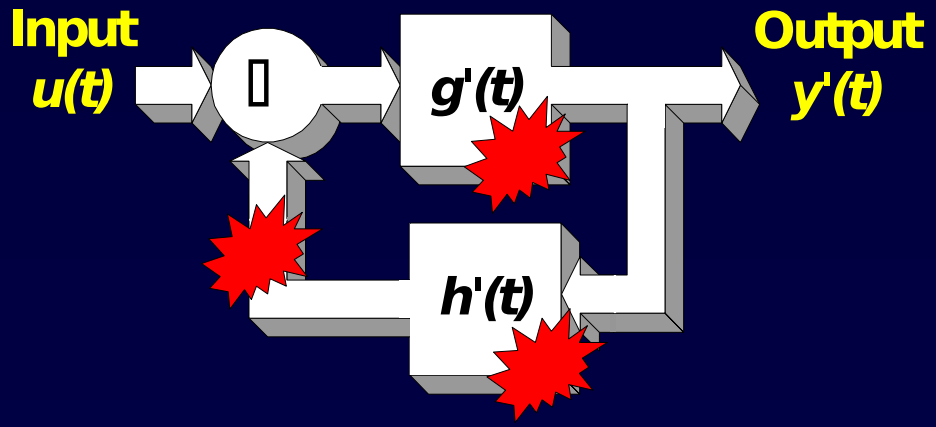
Where $\boldsymbol{\theta}$ represents the scenario; $\boldsymbol{\Omega}$ represents the system configuration; $o_i(t)$, $o_i^*(t)$, $w_i(\boldsymbol{\theta},t)$ and represent the actual & desired state and relative importance of each service.

Dependability: Ability to provide service continuity t
a distribution of likely damage scenarios

Prior Work: ONR Control Challenge Objective

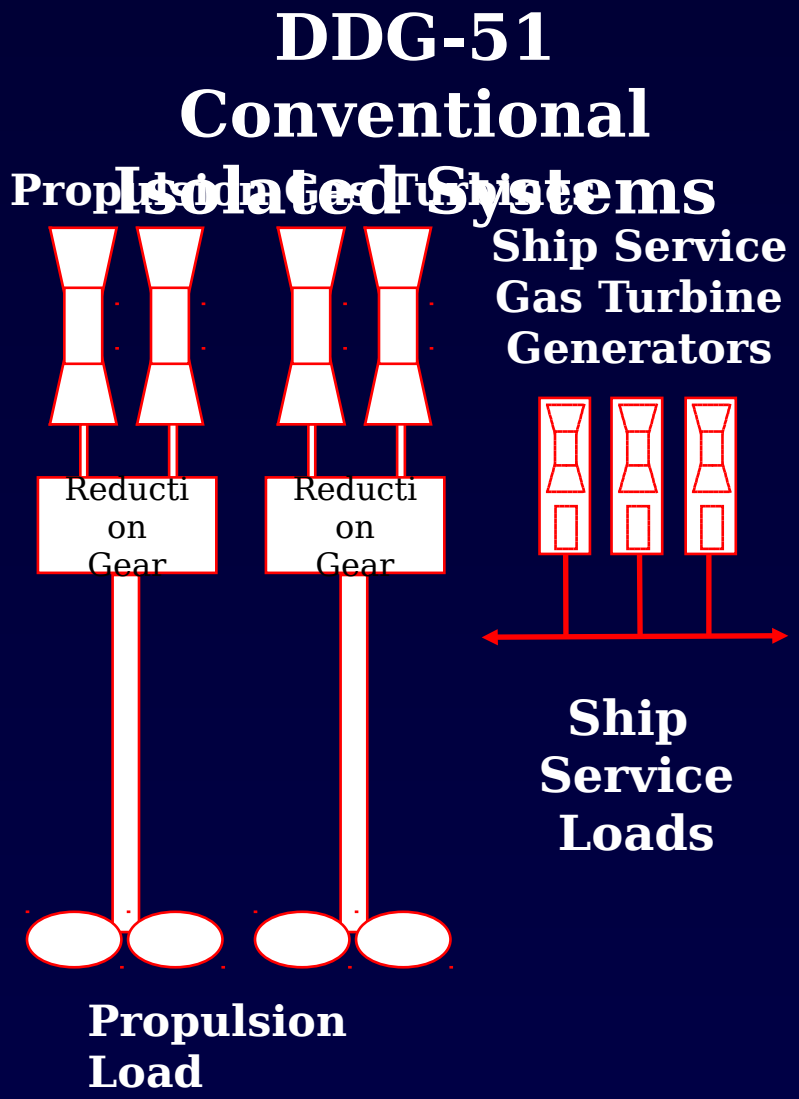
- Continuity of Service Under Temporal And Spatial *Bursts* of Natural or Hostile Disruption.
- Disruption Occurs to Physical Plant, Sensors, Communications, and Control System.

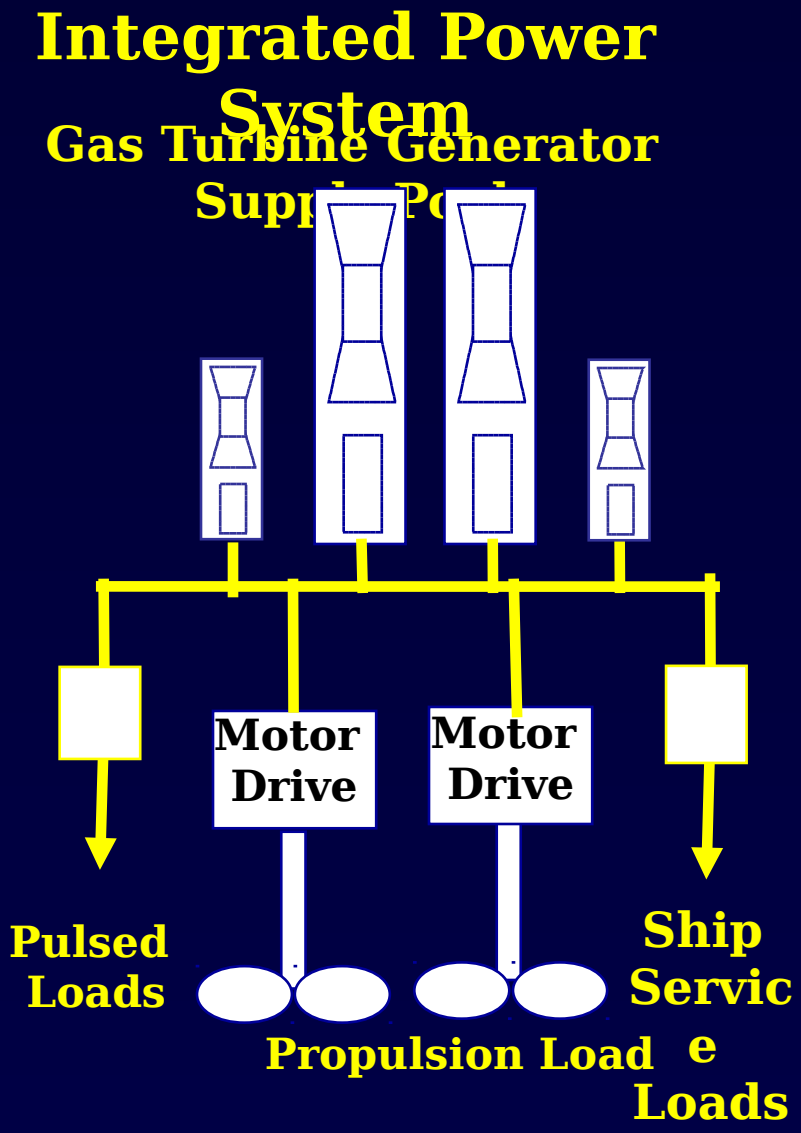




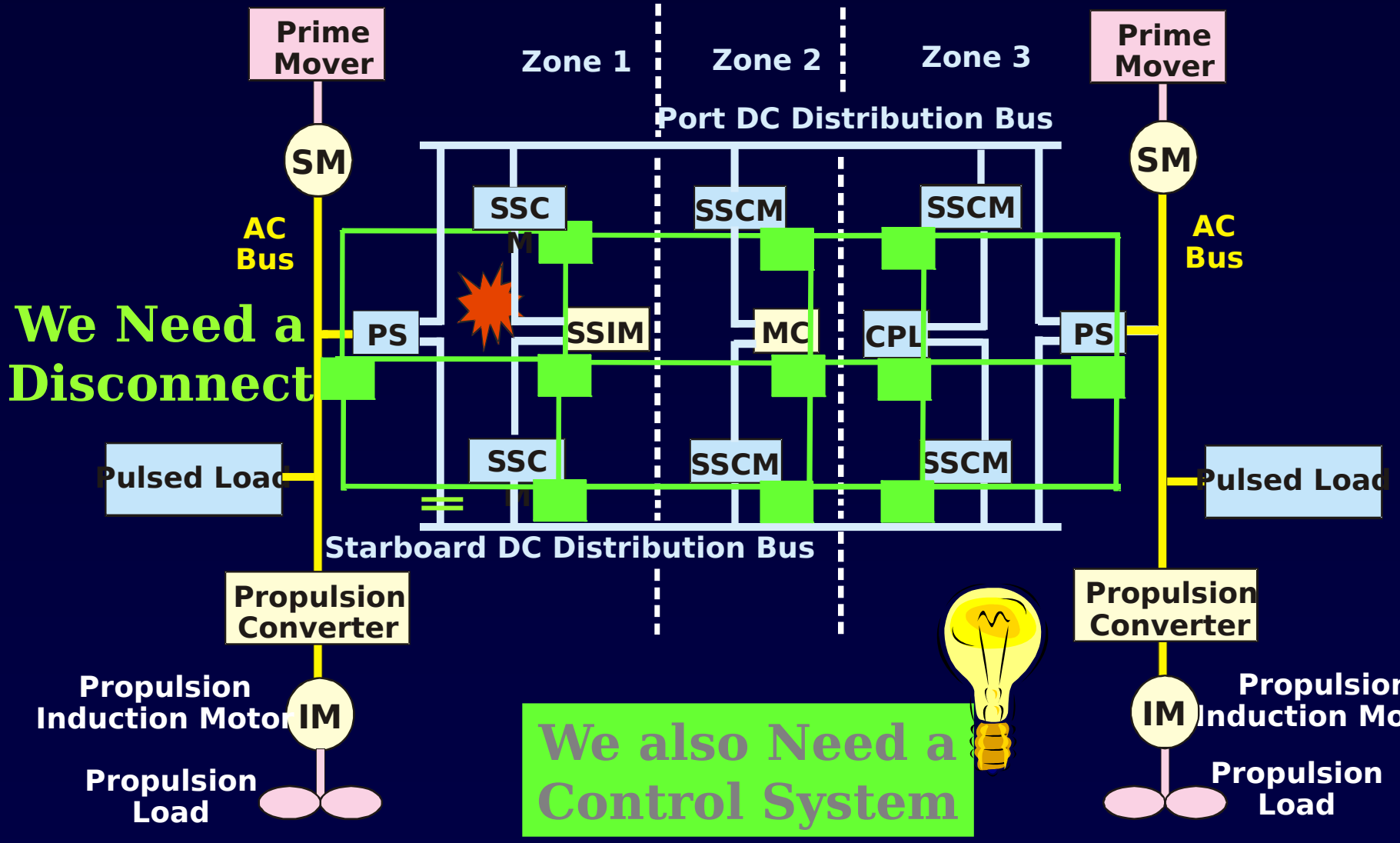
- Maximize True Redundancy
- Minimize Dependencies
- Avoid Common Cause & Common

Related Work: Integrated Power System Transformation





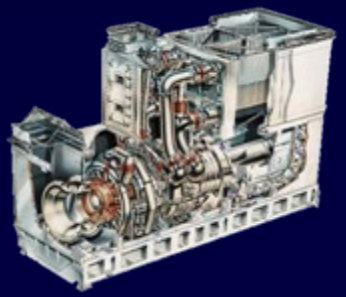
Related Work: Example Zonal Distribution System Disruption



Hierarchical Control Architecture

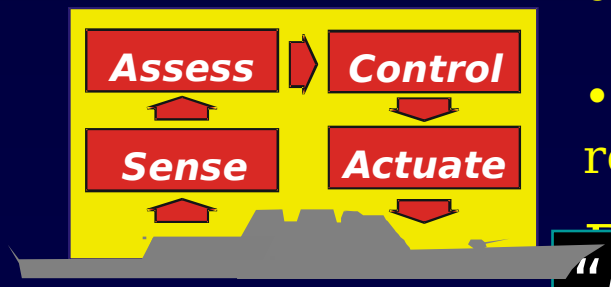
Full Feature Supervisory Control

- Global situational awareness and optimization
- Software only, resides within shipwide C^4I infrastructure
- Flexible cost effective COTS for rapid innovation
- Highly available due to pervasive, distributed redundancy



Intermediate Module or Zonal Control

- Not dependent on supervisory control or communication
- Aligned with construction modules, compartmentation & damage control zones
- Provides subsystem control with analytic redundancy



- Minimal mission / safety critical embedded control

"Utilization without dependence"

IRIS Automation Work in Progress

1. Definition of Baseline Concept of Operations
2. Definition of Baseline Control Architecture & Algorithms
3. Investigation of Alternative Control Algorithms:
   - Observer-based Fault Detection & Isolation
   - Sliding Mode Observers
   - Model-Based Predictive Control
   - Neural-Fuzzy Controls
   - Intelligent Agent Based controls
   - GA-based Controls

Integrated Reconfigurable Intelligent Systems (IRIS)

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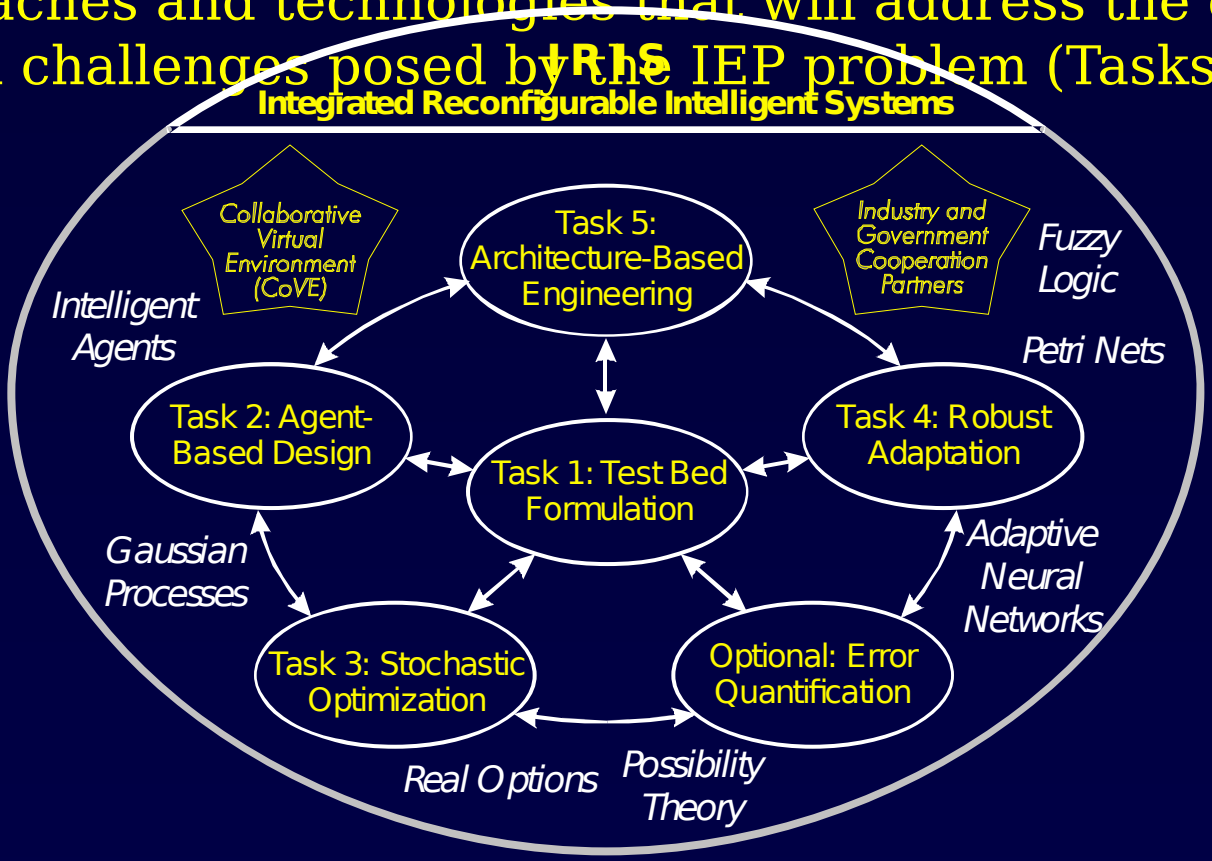
Aerospace Systems Design Lab (ASDL) Research Objectives

- Investigating the application of ASDL's established methodologies to the problem of designing complex naval systems (Task 1)
- Performing basic research into new and innovative approaches and technologies that will address the complex design challenges posed by the IEP problem (Tasks 2 to 5)



ASDL Technical Approach

ASDL is pursuing two concurrent research thrusts

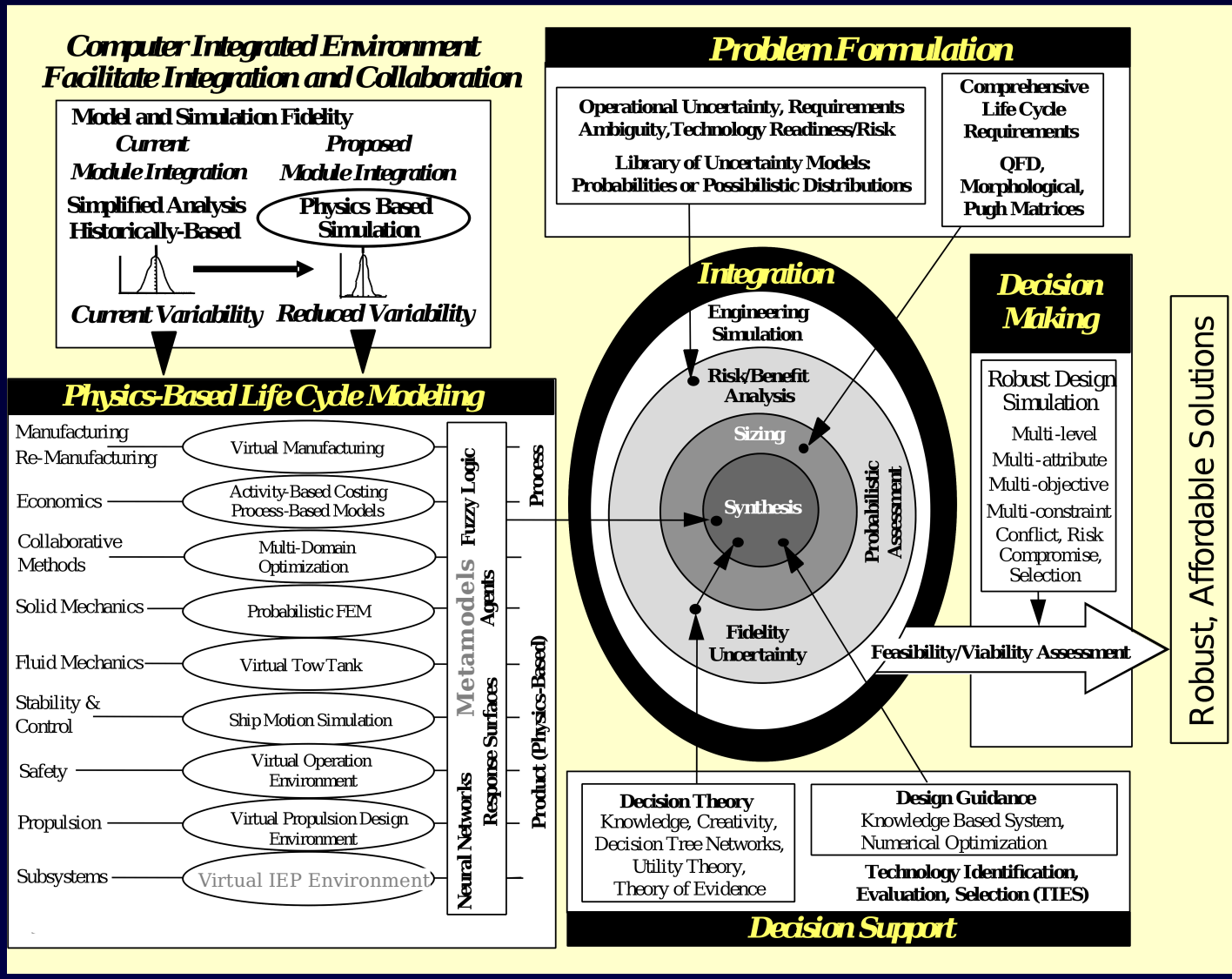
1. An integrated system level simulation testbed is being formulated and implemented through collaboration with university, government, and industry partners, for the purpose of identifying technology gaps and the benefits of potential technologies
2. In parallel, while this environment is being created, a set of potential advanced enabling techniques has been identified and is currently under investigation

Solution: What is IRIS?

- Integrated Reconfigurable Intelligent System
  - A state-of-the-art on-board intelligent computer architecture
  - The focus of IRIS development is on creation of an Integrated Engineering Plant (IEP) modeling and simulation environment
  - The IEP encompasses all electrical, mechanical, and damage control systems
- An IRIS-designed ship will be capable of continuous:
  - Monitoring
    - Capable of Continuous sensing of all ship-related operations
    - Knowledgeable of both current and impending failures
  - Assessing
    - Acquires inputs from all sources and either automatically diagnoses and acts on the best course of action or passes information on to a decision maker
  - Proactive & Reacting
    - Able to distribute power and command as necessary
    - Prepared to compensate and continue to function in the event of system failures

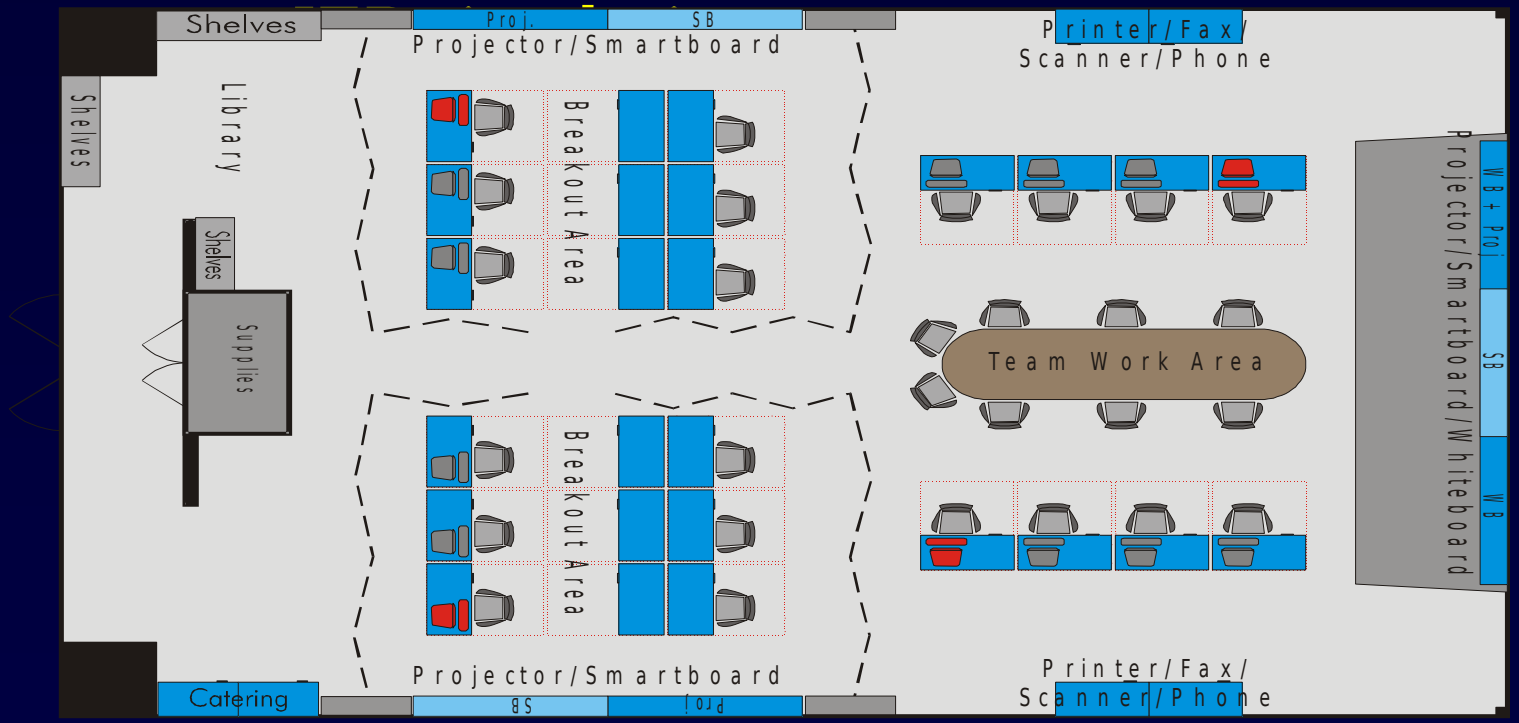
Extension of Existing ASDL System Design Environment

- ASDL has been tasked with creating a computer simulation environment that models the IRIS platform
- ASDL will use physics-based life cycle models to integrate different aspects of the problem
- Throughout the process the inputs of the project partners and independent experts will be vital in arriving at a realistic and highly functional solutions



ASDL Task 1: Simulation Testbed Formulation

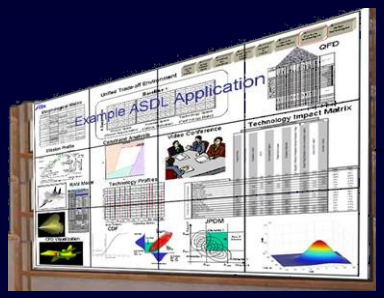
Use ASDL's Collaborative Design Environment (CoDE) to develop and integrate



Concept Enablers:

- Intensive computational facilities for distributed and parallel processing
- Massive storage capacity
- High-speed networking to transmit data

ASDL Task 1: Simulation Testbed Formulation



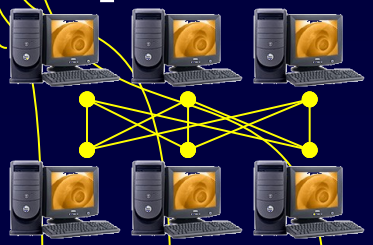
Argus

Display Wall

Gigabit Ethernet

Multi-Terabyte Server

Computational Cluster



File Servers

Tape Backup

- The CoDE is supported by an *intensive computational infrastructure* allowing for:
  - Earlier incorporation of high fidelity physics-based analyses into the design process (e.g., CFD, FE)
  - Real-time linking of engineering design and simulation
  - Distributed computational capability to allow real-time exploration of design space (DOE) and probabilistic analyses
  - An integration of multiple computational platforms needed to support different design tools
  - Massive storage capacity allowing real-time data access and data mining
  - High-speed network to transmit information
- ASDL was awarded a 2004

ASDL Task 1: Simulation Testbed Formulation

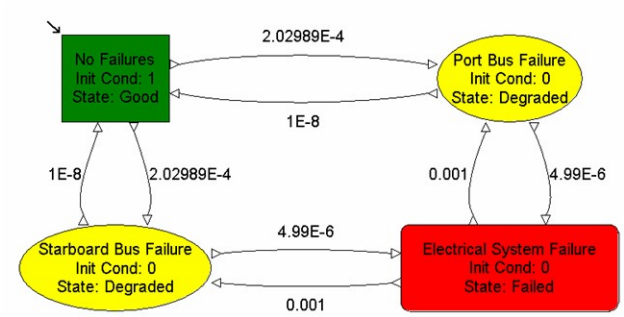
Use Collaborative Visualization Environment (CoVE) as simulation platform

Overarching Theme:

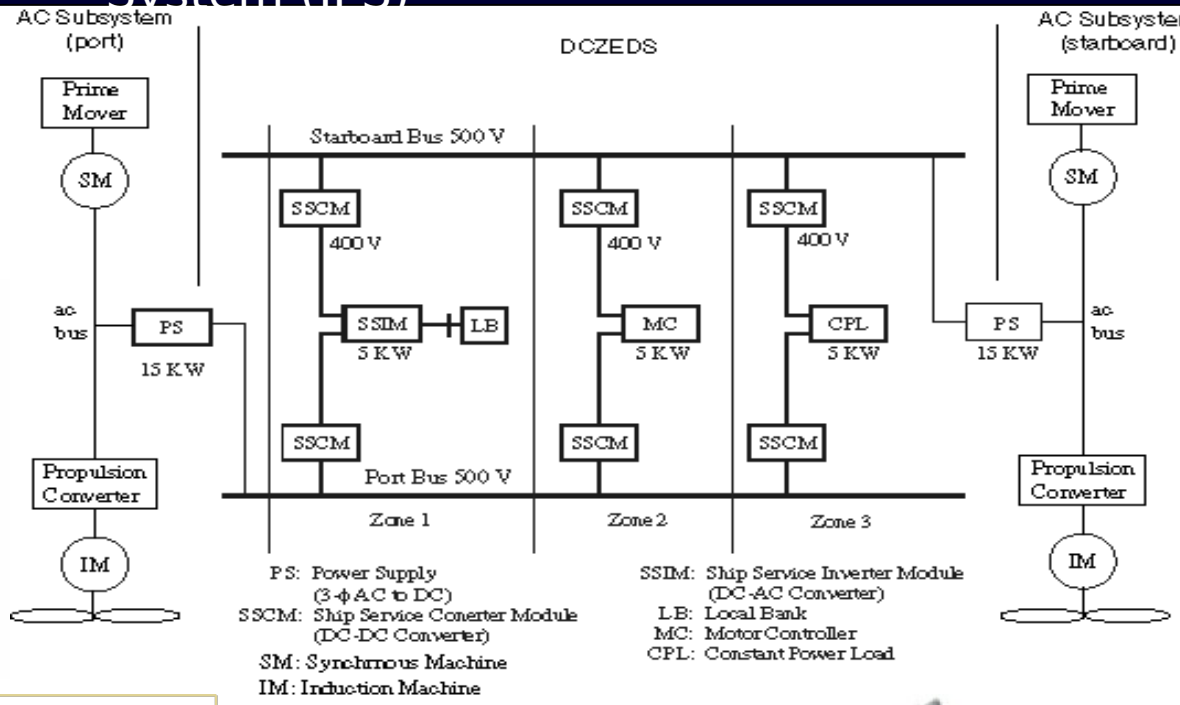
To facilitate the real-time generation, manipulation and display of information and data to produce a collaborative environment for the conceptual design and
nplex

State-of-the-art visualization wall and software creating an environment for advanced multi-attribute decision-making

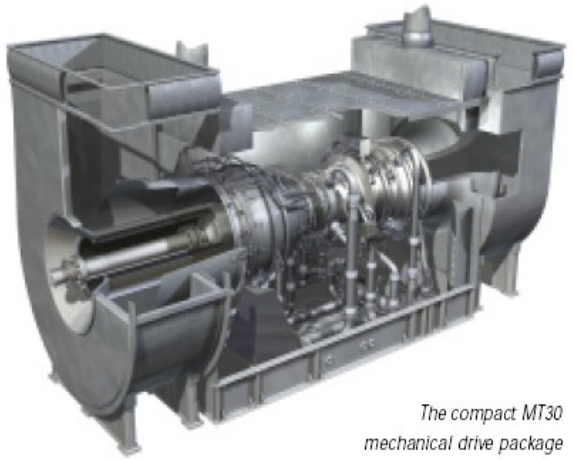
Example of a Reliability Analysis Employing Markov Chains and Petri Nets Using the ONR Control Challenge Reference Integrated Power System (IPS)



A sample Markov chain for electrical failure



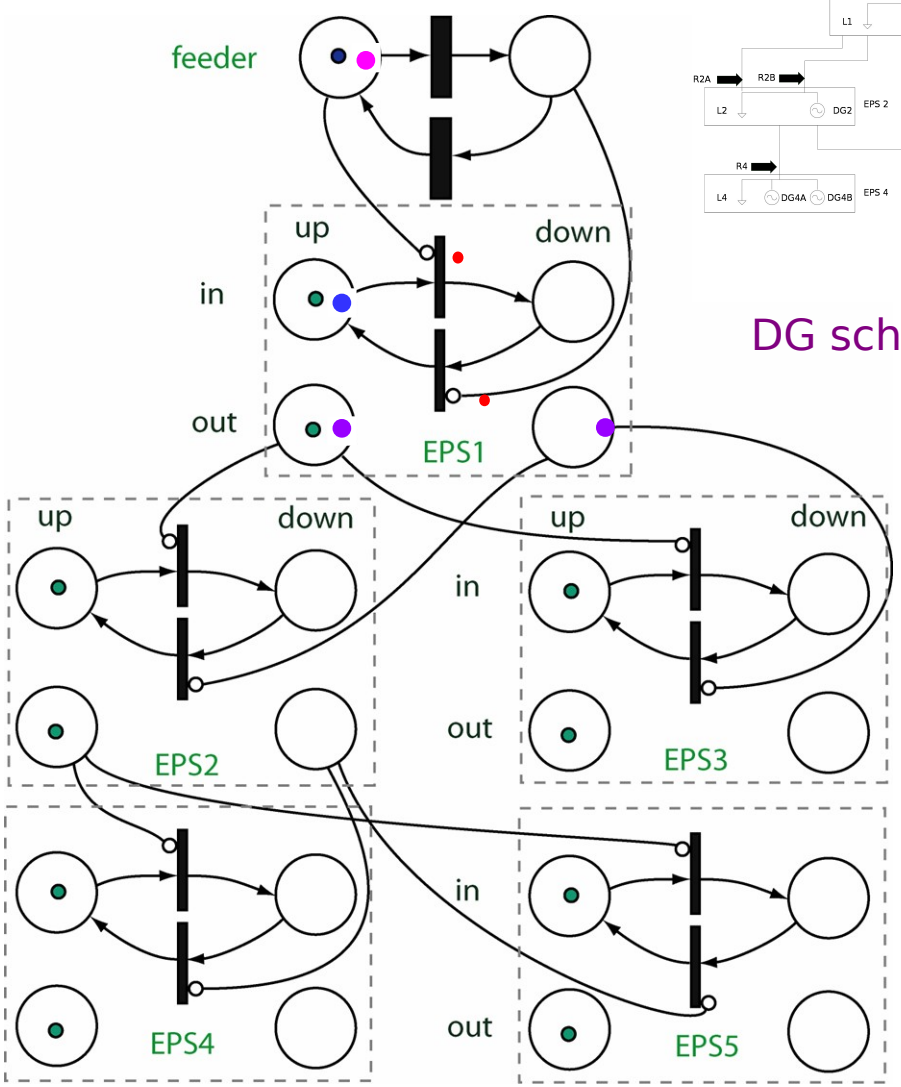
Failure Condition	Phase and Hazard Classification					
	Docked	Cruise	GQ (Surface)	GQ (Air)	Escort	Beach Landing
Bus Power Supply Failure	Minor	Minor	Minor	Minor	Minor	Minor
Propulsion System Failure	Minor	Major	Major	Major	Minor	Minor
Pulsed Load System Failure	Minor	Minor	Major	Major	Minor	Major
Constant Load System Failure	Minor	Major	Major	Major	Major	Major
Single GT Failure	Minor	Major	Major	Major	Major	Major
Dual GT Failure	Minor	Major	Catastrophic	Catastrophic	Catastrophic	Catastrophic

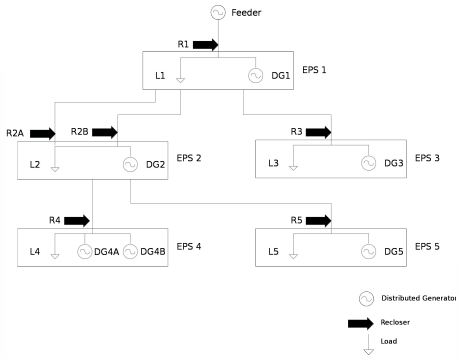


The compact MT30 mechanical drive package

Hierarchical Petri Nets for Distributed Generation Reliability

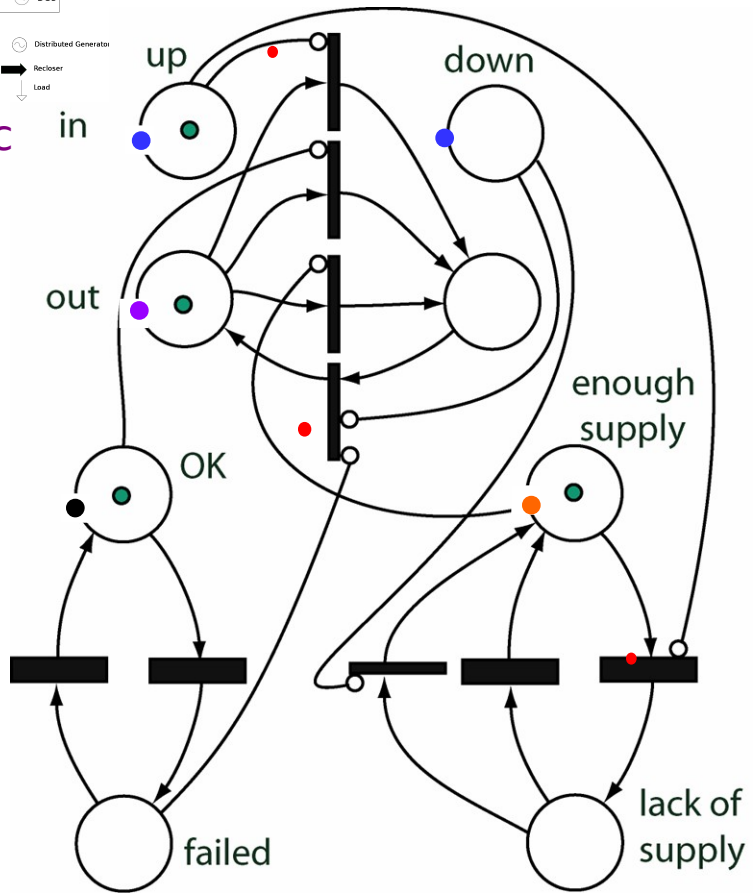
Top level SPN





DG schematic

Local SPN



ASDL Task 2: Agent-based Design

Agent-based modeling and simulation is an approach to study the behaviors and interactions of complex systems. This architecture is based on an agent-system interaction where the agents are software modules that interact with the user.

Explore methods for representing dynamically interdependent system components using "intelligent agents"

- Agents can be used model both humans and electro-mechanical components
- Represent knowledge using sophisticated models where appropriate
- Develop computationally efficient metamodels as surrogates to represent behavioral relationships

ASDL Task 3: Stochastic Metamodeling and Optimization

Sequential Metamodeling (SM) Alternatives Provide Advantages over All-at-Once RSM Modeling

Challenges Encountered for Some Design Problems Using Standard RSM:

- Ranges of variables of interest often lead to non-convergence in significant portions of the design space ***(motivates non-convergence/constraint mapping)***
- Code costly to evaluate ***(motivates efficiency)***
- Simple screening studies unreliable ***(motivates alternate approach to managing dimensionality)***
- Response Surface Methodology exhibits very poor fits for highly nonlinear spaces ***(motivates robust/adaptive metamodeling)***
- System space is "noisy" ***(motivates derivative free methods)***
- Unable to address time-variant system behaviors ***(motivates***

SM algorithms provide alternatives which better address all of these concerns as contrasted to an all-at-once linear multi-variate regression response surface equation approach

ASDL Task 4: Robust Adaptation to Evolving Mission & Operational Environments

Implications of an Uncertain Environment

- Multiple time scales
  - Solutions must be dynamic in nature
- Large changes in the environment will often "break" a chosen system
  - Easily comprehended outcome
  - Short time-scale events are critical
- Small changes can have multiple effects
  - Little or no effect on performance
  - Degraded performance
  - Catastrophic effect on performance

Small and/or Catastrophic Changes are of Most Interest

ASDL Task 5: Architecture-based Systems Engineering

A new paradigm of systems engineering is emerging in the form of a new software design discipline

- An architecture can be defined as *"a description of the fundamental components of a solution and their structural relationships"*
- A strong architecture is the key element in a computer based simulation (CBS) of a complex system
- In order to develop such an architecture, a thorough understanding of the system, its components, and their interrelationships must be achieved
- ASDL/Lockheed-Martin, Fort Worth collaboration

ASDL Task 5: Architecture-based Systems Engineering

Architecture-Based Systems Engineering provides the appropriate environment for the treatment of networked interdependent systems and their dynamics.

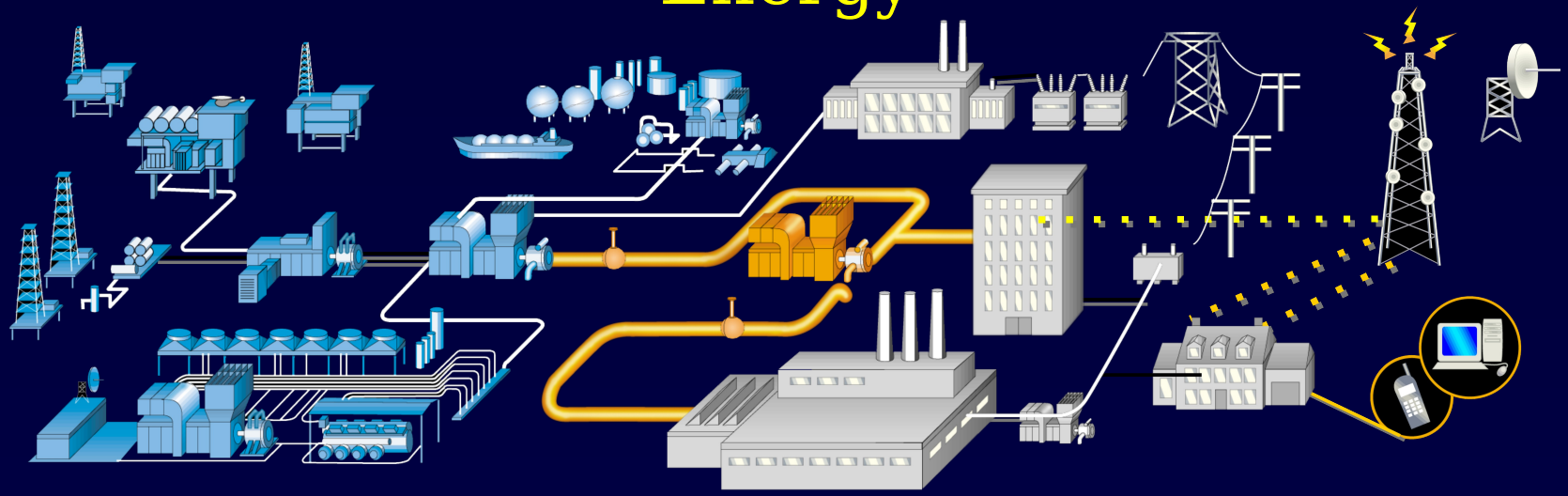
- IEP can be visualized as a complex hierarchical set of interrelationships that can be formulated as a dynamically interdependent system
- Use *object oriented* concepts to decompose and model the system
- Unified Modeling Language (UML) has become the industry standard for the modeling of complex systems

Synergistic Efforts

Leveraged Work

An Integrated Framework for Power Plant Operational Modeling and Optimization

In Collaboration with and Funded by GE Energy

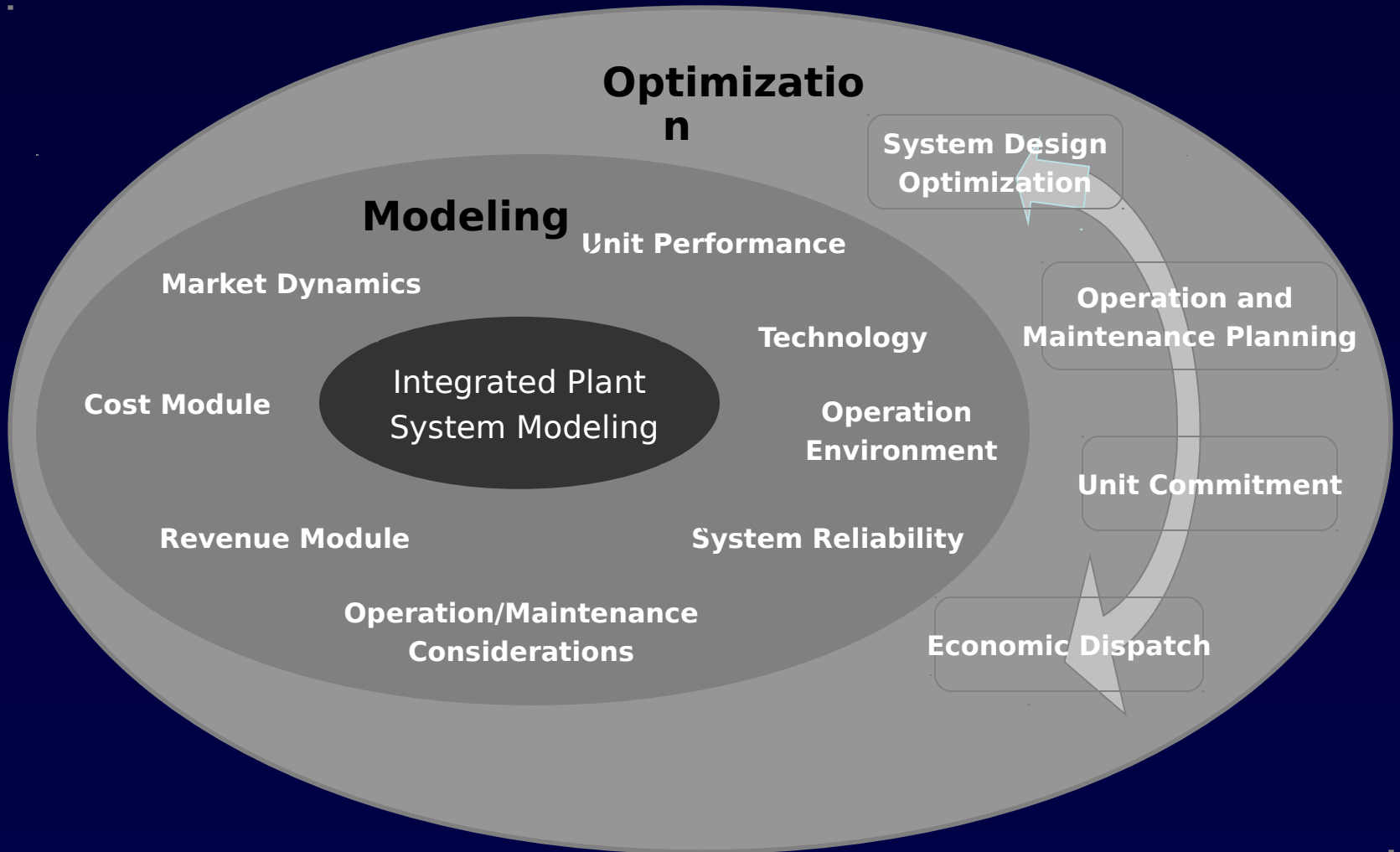


Supply Generation Transmission

Synergistic Efforts

Leveraged Work

Proposed Work: System Modeling, Integration, and Optimization



ASDL Future Plans

- Integration of IEP model components into simulation testbed:
- Develop scenarios:
  - Threat Analysis
  - Collaborate in Operability Analysis
- Application of ASDL methodologies to testbed simulation:
  - Creation of appropriate metamodels for computational efficiency
  - Develop probabilistic formulations for analyses and simulations
  - Agent-based modeling of crew and system components
  - Collaborate in the development and

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Performance Metrics and Their Computation

Recall from before:

- Consider scenario $\boldsymbol{\theta}$
- Consider system $\boldsymbol{\Omega}$
- Operability defined as

$$O(\boldsymbol{\theta},\boldsymbol{\Omega}) = \frac{\int_{t_o}^{t_f} \sum_{i=1}^{I} o_i(t) o_i^*(t) w_i(\boldsymbol{\theta},t) dt}{\int_{t_0}^{t_f} \sum_{i=1}^{I} w_i(\boldsymbol{\theta},t) o_i^*(t) dt}$$

- Evaluation of operability requires a time-domain simulation of the integrated engineering plant

Dependability Metrics

- Dependability is Based on Operability
- System Metrics (for Comparing Systems)
  - D_s : Average Operability for a Single Weapon Detonation
  - $D_{s,mn}$: Minimum Operability for a Single Weapon Detonation
- Architecture Metrics (for Comparing Architectures)
  - Based on Best System Design for that Architecture
  - D_a : Average Operability for a Single Weapon Detonation
  - $D_{a,mn}$: Minimum Operability for a Single Weapon Detonation

System Dependability Statistics

Average Dependability

- The average system dependability (of single weapon impact) is the average operability for a given system over a set of events

$$\bar{D}_s = \sum_{w=1}^{W} \sum_{d=1}^{D} p_{w,d}\, O(\boldsymbol{\theta}, \boldsymbol{\Omega})$$

- Here $p_{w,d}$ is conditional probability of weapon w detonating at point d
- Evaluation requires iterated summation of a function whose evaluation requires a system level time domain simulation

Minimum System Dependability

- The minimum system dependability (of single weapon impact) is the worst case for a given system over a set of events

$$D_{s,mn} = \min_{\boldsymbol{\theta}} O(\boldsymbol{\theta}, \boldsymbol{\Omega}) \quad \boldsymbol{\Omega} \textit{ fixed}$$

- Evaluation requires optimization of a function of whose evaluation requires a system level time-domain simulation

Average Architecture Dependability

- The average system dependability (of single weapon impact) is the average operability for a given system over a set of events, given the system is defined in the best way possible

$$\overline{D}_a = \max_{\Omega} \sum_{w=1}^{W} \int_{volume} p_w(x,y,z) O(\quad,\quad) dv$$

- Evaluation requires optimization of a function involving the iterated summation of another function whose evaluation requires a system level time domain simulation
- Byproduct: Optimal parameter selection

Minimum Architecture Dependability

- The minimum architecture dependability (of single weapon impact) is the worst case for a given system architecture over a set of events, given the system is designed in the best way possible

$$D_{a,mn} = \max_{\boldsymbol{\Omega}} \left\{ \min_{\boldsymbol{\theta}} O(\boldsymbol{\theta}, \boldsymbol{\Omega}) \right\}$$

- Evaluation requires an optimization within an optimization of a function whose evaluation requires a system level time-domain simulation
- Byproduct: Optimal parameter selection

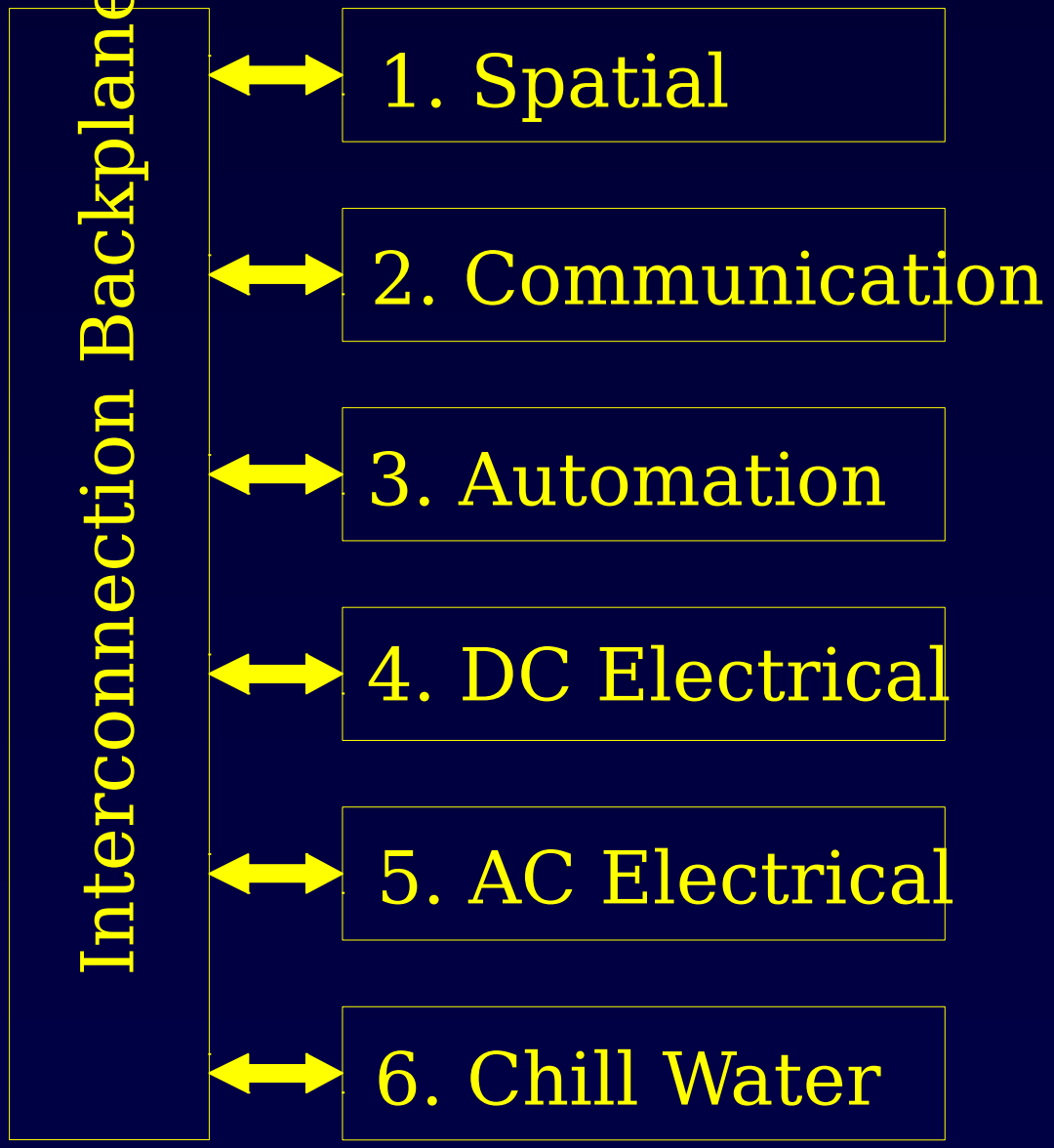
Dependability Calculation Issues

1) Calculating any of these metrics requires calculation of operability. Thus, this is the first order of business.
2) Calculating many of these metric requires iterated summations, optimizations, optimizations-within-optimizations, and combinations thereof. Addressing computational approach is second order of business

Calculation of Operability

- In essence, operability is calculated through time-domain simulation of the integrated engineering plant.
- The integrated engineering plant model most include
  - Spatial Aspects (What survives the detonation?)
  - Automation System (What is the control doing?)
  - Communication System (What links are open?)
  - Power Distribution System (What still has power ?)
  - Cooling Distribution System (What components still have cooling ?)

IEP Model Structure



Software Organization

System Description
Excel / VBA

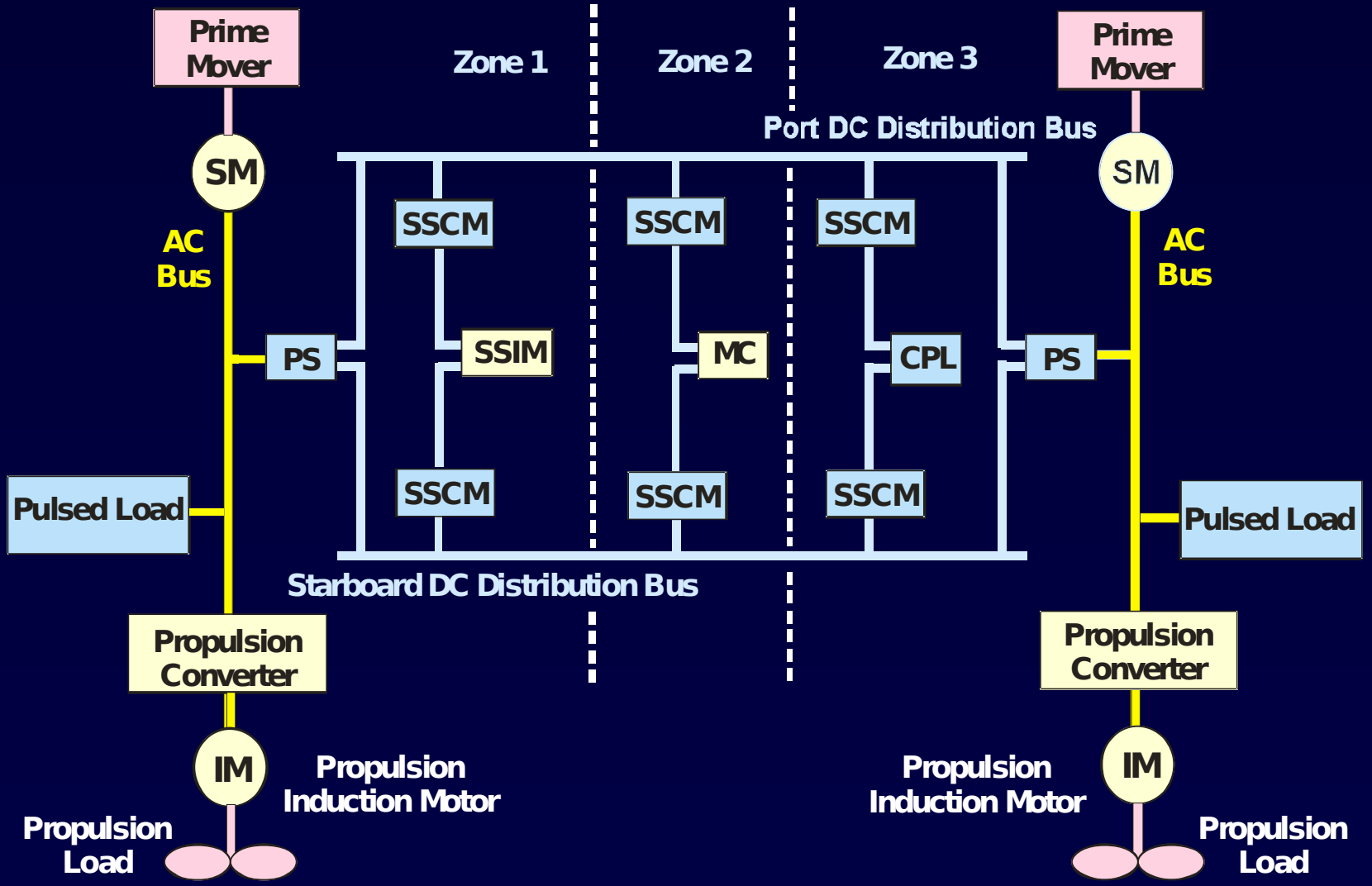
↓

System Simulation
ACSL

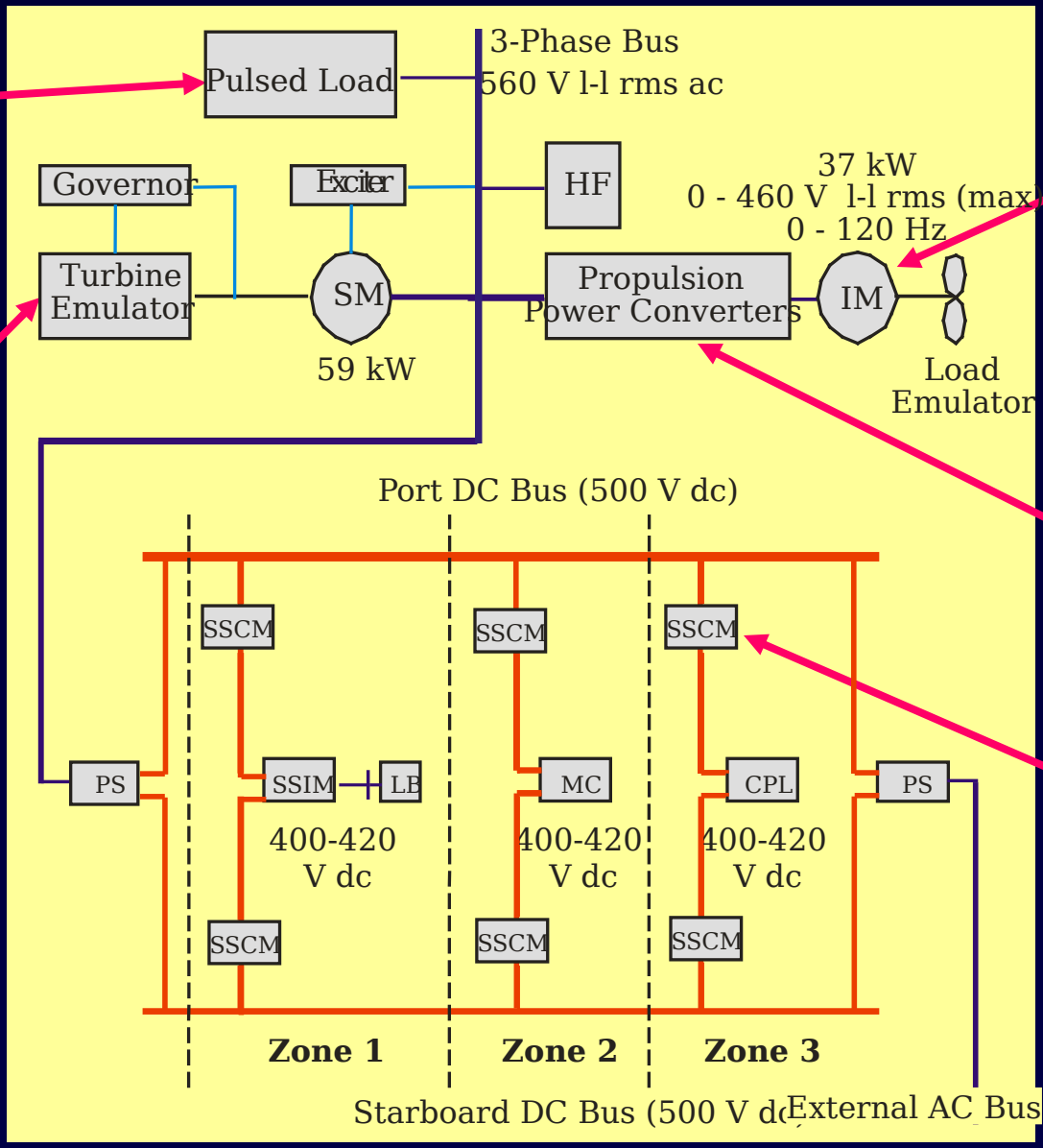
↓

System Assessment
Matlab / GOSET

Strategy: Grow ONR Control Challenge Reference Integrated Power System (IPS) into Notional IEP

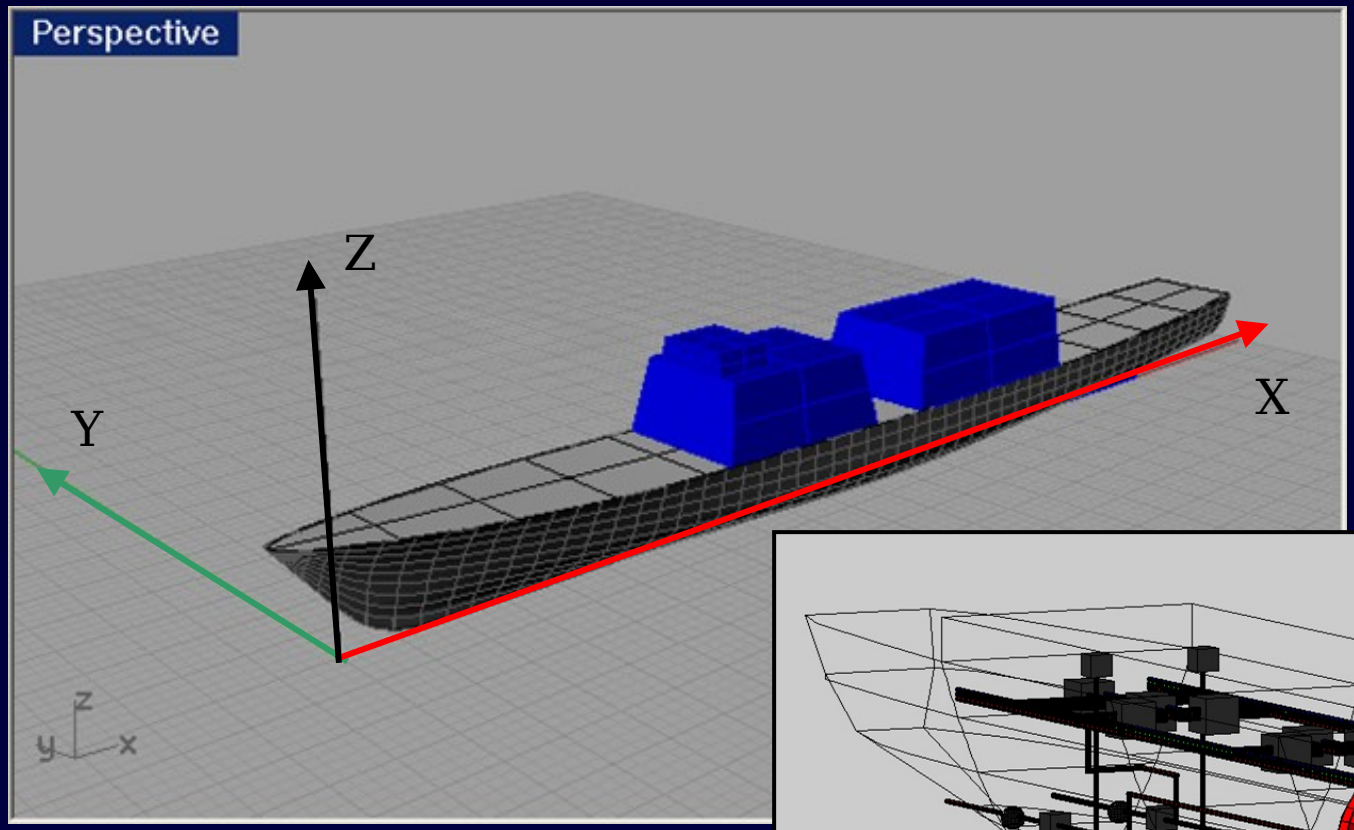


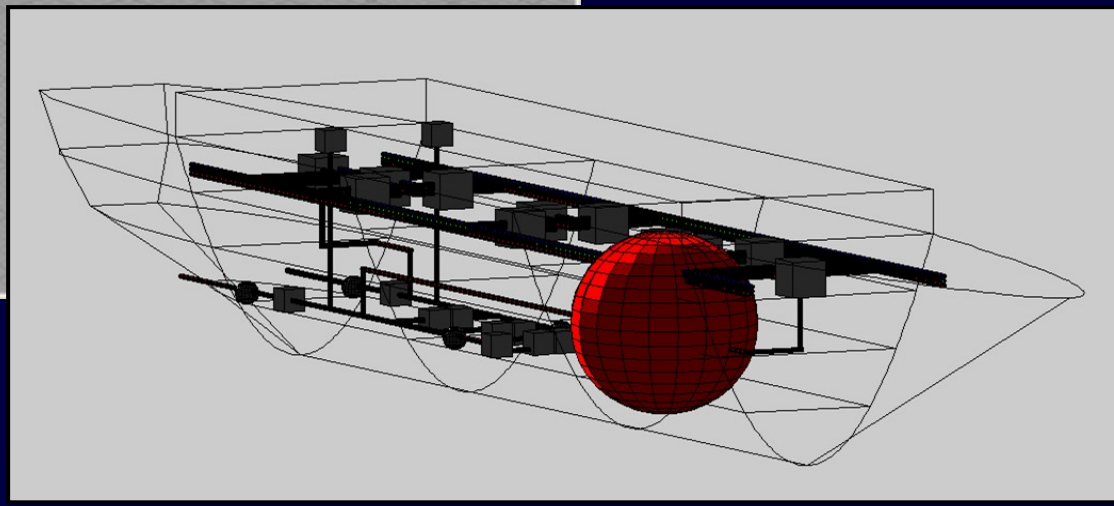
Existing Facility:
Naval Combat Survivability Testbed



IRIS Layer 1 Coordinate System

Development of Layer I Spatial Model comple

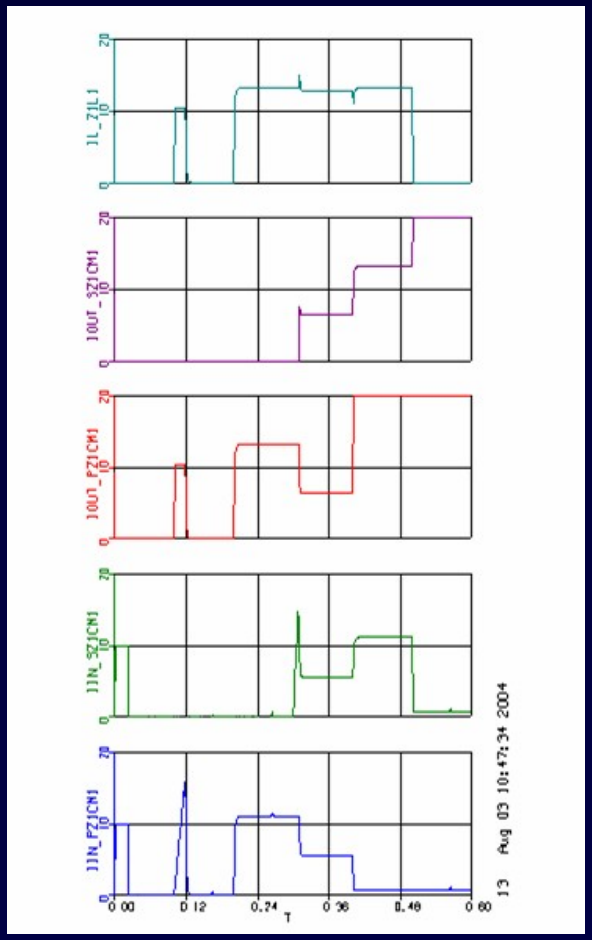


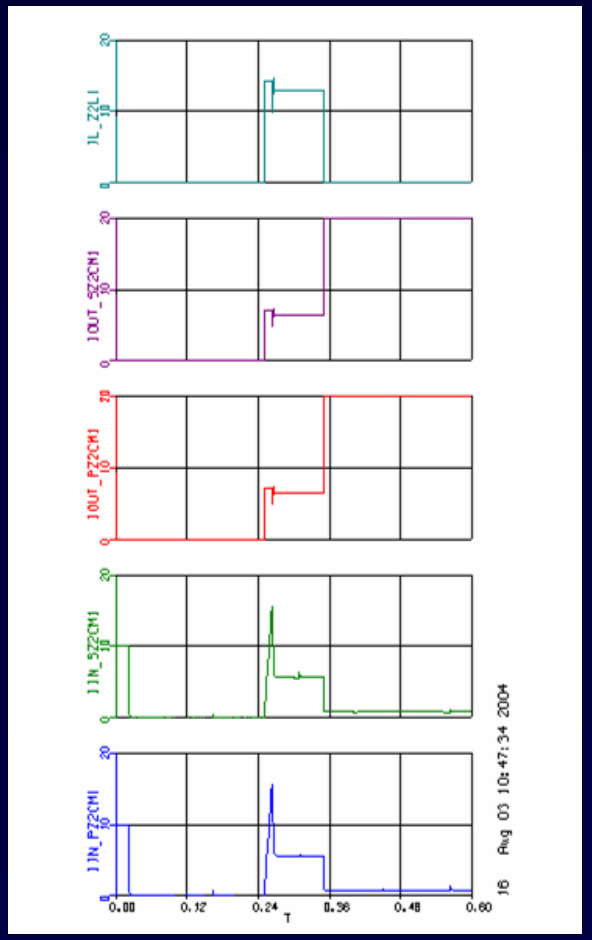


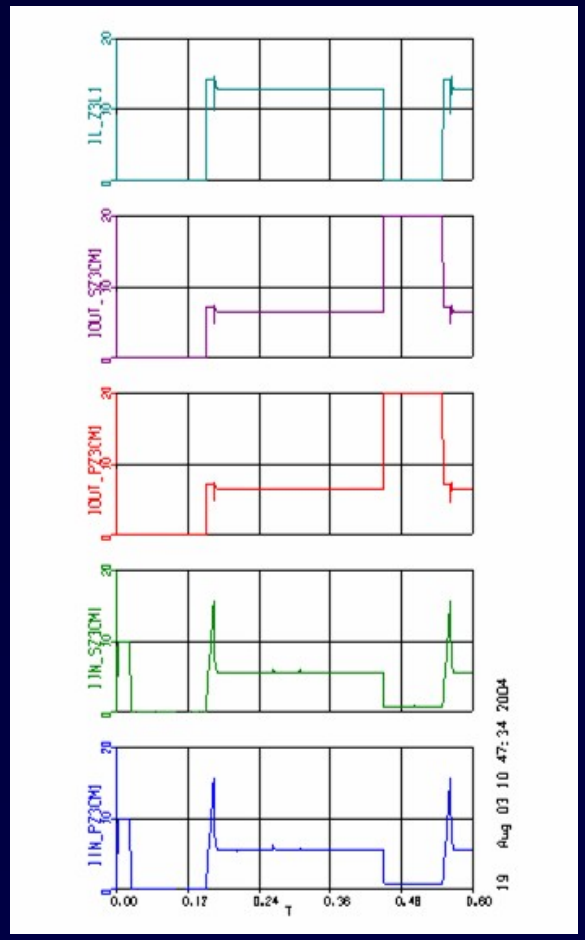
Example Spatial Model

Sample Layer 4 DC Power Simulation Results

39 States, Gears Method, 1.4 times slower than real time on 1.3 GHz Pentium



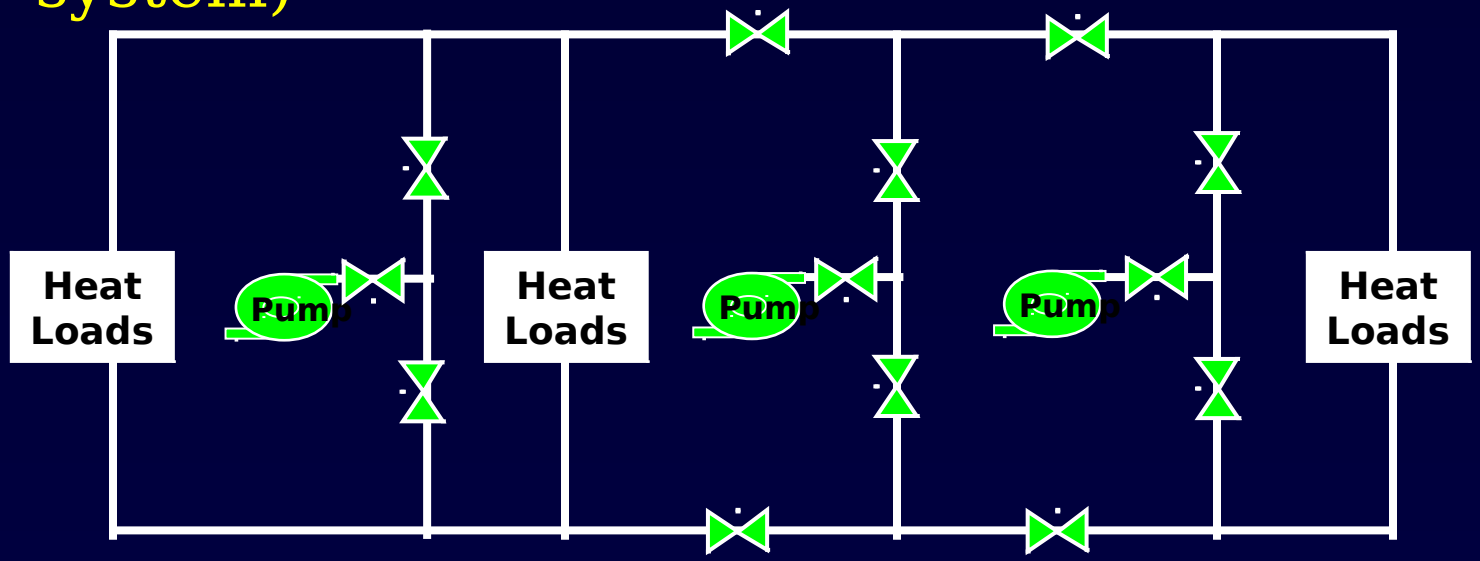




Example operating scenario showing Ship Service Converter Mod

Layer 6: Cooling System

- Initial System Design Complete (3-zone system)



- Component Mathematical Models In Progress:

  Pump, Piping Segment, Piping Junction, Valve & Heat Load

IEP Modeling Status

- Layer 1 (Spatial): Initial spatial model complete
- Layer 2 (Automation): Not started
- Layer 3 (Communication): Not started
- Layer 4: (DC Electric): Initial dc distribution model complete
- Layer 5: (AC Electric) Not started
- Layer 6: (C nulation underway

NCS

	A	B	C	D	E	F	G	H	I	J
1	component									
2	Concatenation	Outputs	Parameters							
3	z	s	xcoord	ycoord	zcoord	deltax	deltay	deltaz		
4	cpz1ps1	s_pz1ps1	5.5	-0.5	0.75	1	1	1		
5	csz3ps1	s_sz3ps1	23.5	-0.5	0.75	1	1	1		
6	cpz1cm1	s_pz1cm1	7.5	-1.75	2	1	1	1		
7	csz1cm1	s_sz1cm1	7.5	0.75	2	1	1	1		
8	cpz2cm1	s_pz2cm1	13.5	-1.75	3.25	1	1	1		
9	csz2cm1	s_sz2cm1	13.5	0.75	3.25	1	1	1		
10	cpz3cm1	s_pz3cm1	19.5	-1.75	4.5	1	1	1		
11	csz3cm1	s_sz3cm1	19.5	0.75	4.5	1	1	1		
12	cz1l1	s_z1l1	9.5	-0.5	2	1	1	1		
13	cz2l1	s_z2l1	15.5	-0.5	3.25	1	1	1		
14	cz3l1	s_z3l1	21.5	-0.5	4.5	1	1	1		
15										
16										

Component / Connection / Segment / Load / Power Supply / Converter / PDCB / ZDCB /

Example Excel Configuration Spreadsheet

IRIS Computational Optimization

- Beyond calculating operability, many of the proposed performance indices require solution of an optimization problem.
- We have a noise objective function
- We have a large search space
- Anticipated approach: genetic algorithms

Genetic Optimization Tools

Genetic Optimization System Engineering Tool

⇔

216 Processor Computational Array

IRIS MIT Ship Design Math Model

- Completed ship design model translation to Matlab in collaboration with Purdue
- Validated ship design model
- Provided GA-enabled version to team members

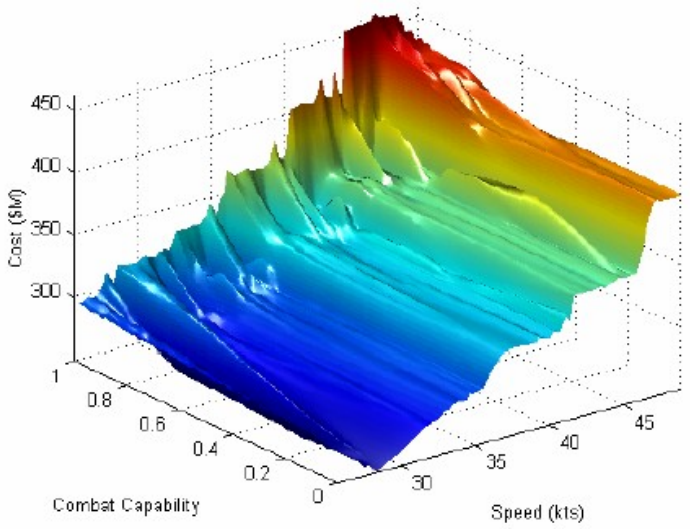


Figure 5. Pareto Front of Speed, Combat Capability, and Cost for designs with Range Over 5000nm

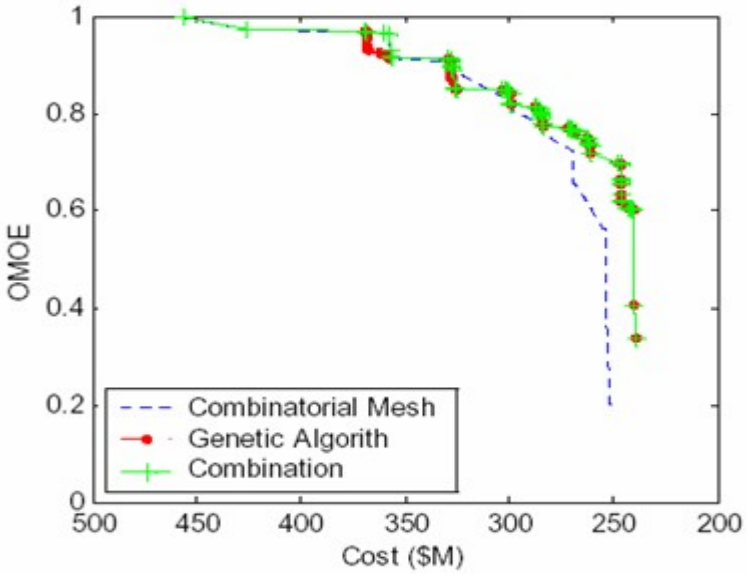


Figure 6. Pareto Front of OMOE vs. Cost Using Two Methods

From Wolf, et. al.

Product Description

Design Methods and Computational Tools for Early Design Tradeoffs of Alternative System Architectures, Technologies, and Configurations of Dynamically Independent Subystems

Exit Criteria

Proof of Concept Design Example for Notional Electric Warship

Transition Targets

1. USN Ship Design Community
   Example: Center for Innovative Ship Design
2. Shipyards and Ship Systems

Status

On Schedule, on Budget, year 1 of 3

Questions?

Research Thrust Synopsis

USNA, MIT & Purdue

Thrust 1: Distributed Automation System Design

Thrust 2: Automation Concepts and Technology

Thrust 3: Computational

Georgia Tech

Thrust 1: Testbed Formulation

Thrust 2: Agent Based Design

Thrust 3: Stochastic Optimization

Thrust 4: Robust Adaptation